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115 Gbit/s downstream and 10 Gbit/s upstream TWDM-PON together with 11.25 Gbit/s wireless signal utilizing OFDM-QAM modulation

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ABSTRACT

In this work, we propose and investigate a 115 Gbit/s (4×28.75 Gbit/s) downstream and 10 Gbit/s upstream time- and wavelength-division-multiplexing passive optical network (TWDM-PON) together with 11.25 Gbit/s wireless broadcasting signal using multi-band orthogonal-frequency-division-multiplexing (OFDM) modulation within 10 GHz bandwidth. Here, to compensate the power fading and chromatic dispersion in the higher frequency, we utilize a −0.7 chirp parameter Mach–Zehnder modulator (MZM) for the OFDM signal. Hence, negative power penalties of −0.3 and −0.4 dB in the downstream and broadcasting wireless signals; and power penalty of 0.3 dB in the upstream signal are measured at the bit error rate (BER) of 3.8×10^{-3} after 20 km standard single mode fiber transmission without dispersion compensation.

1. Introduction

High-speed and high-capacity passive optical networks (PONs) are promising access systems to provide wide bandwidth to end users economically [1,2]. However, in future next generation (NG)-PON, the downstream traffic rate of 40 Gbit/s or even beyond 100 Gbit/s is required owing to the requirement of different broadband multi-service [3–5]. To achieve 40 Gbit/s passive access, using single wavelength with 40 Gbit/s orthogonal frequency division multiplexing (OFDM); and time- and wavelength-division-multiplexing (TWDM) with 4×10 Gbit/s on–off keying (OOK) has been proposed [6,7]. Thus, for the 40 Gbit/s PON access, using OOK modulation on single wavelength in standard reach PON transmission (20 km) is no longer feasible due to the constrains of fiber chromatic dispersion, polarization mode dispersion (PMD), and expensive 40 GHz transceiver [5].

For the future 40–100 Gbit/s PON, to obtain higher traffic rate cost-effectively, the high spectral efficiency of OFDM-QAM modulation would be used [8,9]. Recently, 40 Gbit/s OFDM-PON has also been investigated by using broadband OFDM signal [10,11]. However, they required the higher sampling rate of 12 GS/s of digital to analog/analog to digital (DA/AD) conversion for OFDM processing. Besides, the OFDM subcarriers would also be affected in the higher frequency due to the chromatic dispersion and RF power fading. Therefore, using the positive chirp modulator would enhance the effect of the fiber dispersion and power fading.

OFDM-QAM is a spectral efficient modulation format in which the data is encoding on multiple subcarriers, and the subcarriers are orthogonal to one another. On the other hand, TDM and WDM allow time and wavelength multiplexing of different channels respectively; hence allowing different users to access and share the same communication link. Besides TDM and WDM, OFDM can provide one more degree of freedom by providing sub-wavelength signal multiplexing via orthogonal frequency division multiple access (OFDMA) [12].

In this demonstration, we proposed and investigate a 115 (4×28.75) Gbit/s downstream and 10 Gbit/s upstream TWDM-PON utilizing multi-band OFDM modulation together with 11.25 Gbit/s wireless broadcasting signal. Here, the proposed TWDM-PON with multi-band OFDM modulation is operated within 10 GHz bandwidth. Each OFDM band is modulated at 16-QAM format. Then, the multi-band OFDM channels of each downstream wavelength are employed in 10 GHz bandwidth Mach–Zehnder modulator (MZM) with −0.7 chirp parameter to generate the 28.75 Gbit/s downstream data and 11.25 Gbit/s wireless traffic in the central office (CO). Direct detection is employed to reduce the cost of receiver (Rx) module. Besides, each 16-QAM OFDM band only needs a 5 GS/s sampling rate and 8 bits resolution for DA and AD conversions in practical system to achieve cost-effectiveness. Furthermore, the continuous wave (CW) wavelength in the CO is distributed to the 2.5 GHz bandwidth Fabry–Perot laser diode (FP-LD)-based optical networking unit (ONU) for upstream 16-QAM OFDM modulation. From the experimental results, the

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downstream and broadcasting wireless negative power penalties of −0.3 and −0.4 dB and upstream penalty of 0.3 dB are observed simultaneously, at the bit error rate (BER) of 3.8×10^{-3} after 20 km single mode fiber (SMF) transmission without dispersion compensation due to pre-chirp characteristic of MZM.

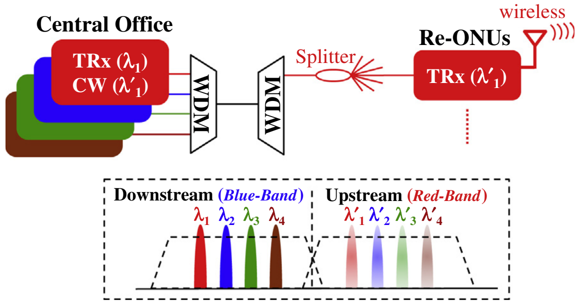

Fig. 1. Proposed TWDM-PON architecture by using multi-band OFDM modulation architecture. The inset is the proposed wavelength assignment for the downstream and upstream signal.

2. Experiment and discussions

Fig. 1 shows the proposed TWDM-PON architecture using multi-band OFDM modulation architecture. Here, in the CO, four WDM wavelengths (λ_1, λ_2, λ_3, and λ_4) are utilized for 115 Gbit/s downstream and 11.25 Gbit/s wireless broadcasting signals. Besides, four WDM CW wavelengths (λ'_1, λ'_2, λ'_3, and λ'_4) are used to distribute into each ONU for upstream modulation to achieve colorless operation. In addition, the proposed wavelength assignment for the downstream (blue[1]-band) and upstream signal (red-band) is also illustrated in Fig. 1. The downstream wavelengths and the upstream wavelengths are spaced by one free spectral range (FSR) of the arrayed waveguide grating in the C-band. Hence, one port of the arrayed waveguide grating can support the two wavelength signals simultaneously due to the spectral periodicity property. There are two methods that can achieve single side band optical signal. The first is using optical IQ modulator which is much expensive then a MZM. The second method is using optical filter. And the signal needs guard band due to the non-ideal transition edge of the filter, it would reduce the bandwidth efficiency and increase the cost of the system.

Fig. 2 presents the experimental setup of proposed TWDM-PON system together with wireless broadcasting. In this measurement, a 1540.2 nm wavelength is used to connect to MZM for downstream modulation. The downstream wavelength will transmit through a blue-/red-band filter (BRF), erbium-doped fiber amplifier (EDFA), a 20 km SMF and a BRF, and then is received by 10 GHz PIN Rx for signal demodulation, as seen in Fig. 2.

Fig. 2 also shows the schematic spectra of the four-band OFDM modulation for downstream and wireless traffics. Here, the band_1 OFDM signal has the bandwidth of 1.526 GHz. The band_2 to band_4 are with the same bandwidths of 2.813 GHz and are up-converted to the frequencies of 3.164, 6.055 and 8.945 GHz by using I-Q modulation, respectively. Here, we used the 4-port IQ mixer from Hittite. The RF bandwidths and conversion losses of IQ mixers from band_2 to band_4 are 1 MHz-6 GHz, 4–8.5 GHz and 6–10 GHz, and 7, 7.5 and 7 dB, respectively. Besides, the OFDM band separations are 0.1315, 0.078 and 0.077 GHz respectively.

In this experiment, owing to the limitation of available equipment, the measurement of the four-band OFDM signals are separated into two parts, as illustrated in Fig. 2. In the first part, band_1 and band_2 are generated by the arbitrary waveform generator_1 (AWG_1) and arbitrary waveform generator_2 (AWG_2). In the second part, band_3 and band_4 employ the same AWG_2. Hence, the total multi-band OFDM bandwidth is 10.3515 GHz, which can fit into the modulation bandwidth of our 10 GHz MZM. Besides, since each band is set to be orthogonal with one another, there is almost no interference among the adjacent band.

Fig. 2 indicates that the first part includes band_1 and band_2 (Ch_1 and Ch_2) signals, and the second part includes band_3 and band_4 signals for the practical downstream OFDM measurements. Here, the band_1 to band_3 are utilized for the downstream data, and the band_4 is used for broadcasting wireless signal. Moreover, the four-band OFDM signals are using the same modulation of 16-QAM with a fast-Fourier transform (FFT) size of 512 and cyclic prefix (CP) size of 8 (including 7% overhead). The OFDM signals are generated by AWG by using the Matlab® program. In the proposed OFDM system, the sampling rate and DA/AD resolution of 5 GS/s and 8 bit are utilized, respectively. As shown in Fig. 2, base-band OFDM signal of band_2 to band_4 are IQ modulated by the IQ mixer.

In the first part, the band_1 OFDM signal is generate by AWG_1. It contains 40 OFDM subcarriers occupying 1.526 GHz bandwidth from 82 MHz to 1.626 GHz to produce a total data rate of 6.25 Gbit/s. The band_2 OFDM signal consist 72 subcarriers occupying 2.813 GHz bandwidth to generate a data rate of 11.25 Gbit/s. In the second part, the band_3 and band_4 OFDM signals are generated by using AWG_2, and each band also consists of 72 OFDM subcarriers occupying 2.813 GHz bandwidth for producing a data rate of 11.25 Gbit/s. The multi-band OFDM signal could be applied to the MZM with the alpha chirp parameters of −0.7. As a result, the downstream data of 28.75 Gbit/s and broadcasting wireless of 11.25 Gbit/s at 8.945 GHz can be generated simultaneously by the proposed four-band OFDM modulation.

In the experiment, one 3 GHz bandwidth LPFs is employed for band_1, four 1.9 GHz bandwidth LPFs are used for band_2 to band_4, and three BPFs with 3.4 GHz bandwidth are utilized for band_2 to band_4, as shown in Fig. 2. After 20 km SMF transmission, the 28.75 Gbit/s downstream and 11.25 wireless signals are directly detected by a PIN Rx. The PIN Rx has a 3 dB bandwidth of 12 GHz. It has the responsivity of 0.9 A/W at wavelength of 1550 nm. The dark current is about 5 nA. Besides, a real-time scope is used to capture the received electrical data for off-line analysis. Therefore, the BER would be calculated according to the measured signal-to-noise ratio (SNR) of each OFDM subcarrier.

As we know, the SNR of OFDM subcarrier would drop seriously in high frequency after a length of fiber transmission due to the RF power fading [13]. Here, to realize the relationship of chirp effect and OFDM signal, first we use a 0.53 chirp parameter of electro-absorption modulator (EAM) to experiment the four-band OFDM modulation. First, we use the numerical analysis of RF power fading at the chirp parameter of 0.53 and −0.7 respectively. Fig. 3 presents the numerical result of the power fading under the frequencies from 0 to 10 GHz, when the chirp parameter is 0.53 and −0.7 respectively, after 20 km SMF transmission. As seen in Fig. 3, the power fading could be improved in the higher frequency when the negative chirp parameter is employed. When the frequency is 10 GHz under the 0.53 and −0.7 chirp parameters, respectively, the power fading can be obtained in −28.8 and −3.8 dB.

Fig. 4(a) and (b) presents the measured SNR of each OFDM subcarrier at the back-to-back (B2B) and 20 km SMF transmission under the received power of −10 dBm, when the 0.53 chirp parameter EAM and −0.7 chirp parameters MZM is utilized respectively. As shown in Fig. 4(a), the SNR cannot achieve the forward error correction (FEC) threshold (SNR = 16.5 dB; BER = 3.8×10^{-3}) after 20 km fiber transmission, when the OFDM subcarrier

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[1] For interpretation of color in Figs. 1 and 2, the reader is referred to the web version of this article.

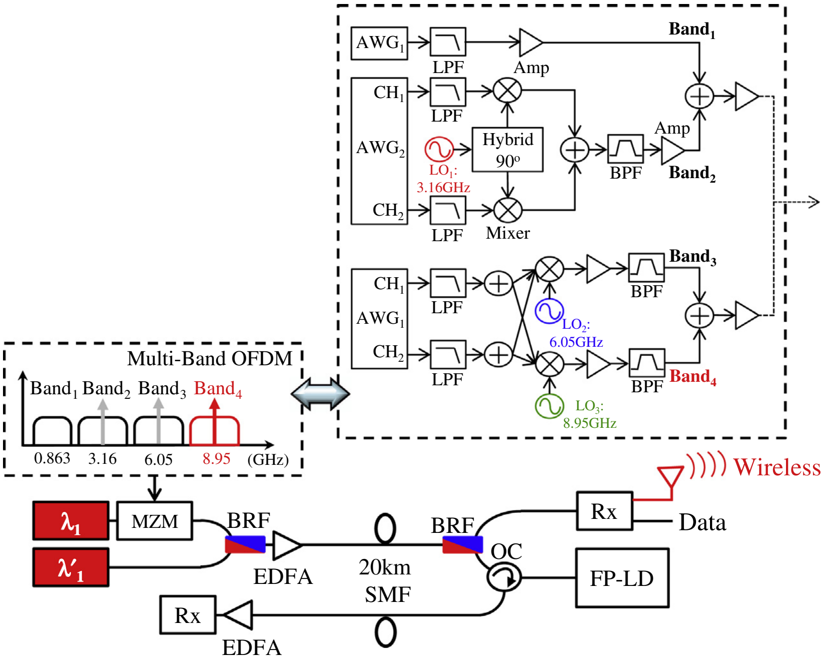

Fig. 2. Experimental setup of proposed TWDM-PON system together with wireless broadcasting, and the schematic spectra of the four-band OFDM modulation for downstream and wireless traffics.

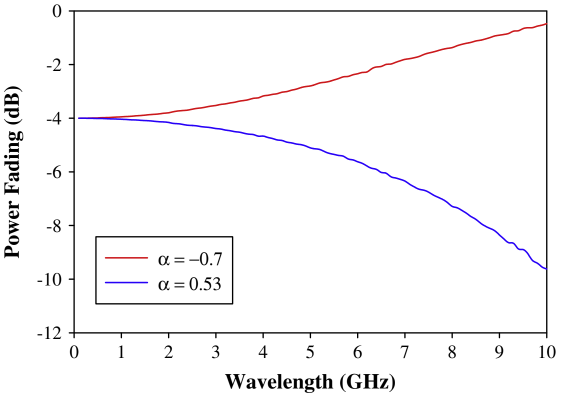

Fig. 3. The numerical result of the power fading under the frequencies from 0 to 10 GHz, when the chirp parameter is 0.53 and −0.7 respectively, after 20 km SMF transmission.

frequency is larger than 7.2 GHz due to power fading and chromatic fiber dispersion. Moreover, the band$_4$ (wireless signal) would be influenced and become worst in 20 km fiber transmission.

To solve the issue, while maintaining the 20 km reach of the standard PON together with wireless signal transmission, a 10 GHz MZM with −0.7 chirp parameter is used. The MZM (produced by *Eospace*) is Z-cut with a fixed pre-chirp alpha chirp parameter of −0.7. The insertion loss and the V_{pi} of the MZM are 3 dB and 4 V, respectively. Fig. 4(b) shows the SNR of each OFDM subcarrier under the four-band frequency at the B2B and 20 km fiber transmission when the received power is −10 dBm. The observed SNR of band$_3$ and band$_4$ are increased due to pre-compensation via pre-chirp MZM after 20 km SMF transmission, as shown in Fig. 4(b). Moreover, after 20 km transmission, the measured SNRs of OFDM subcarriers in band$_3$ and band$_4$ are better than that of B2B status, as seen in Fig. 4(b). Besides, the measured SNRs of all four-band OFDM frequency are larger than FEC threshold. Fig. 5 presents the measured electrical power of four-band OFDM at the B2B status and 20 km fiber transmission. Due to the pre-chirp of MZM in the experiment, the power gain in the OFDM signal of band$_3$ and band$_4$ can be enhanced after 20 km fiber transmission, as shown in Fig. 5. Therefore, the pre-chirp MZM is very crucial for the proposed 115 Gib/s TWDM-PON architecture with 8.945 GHz wireless signal by employing multi-band OFDM modulation to reduce power fading in 20 km SMF transmission.

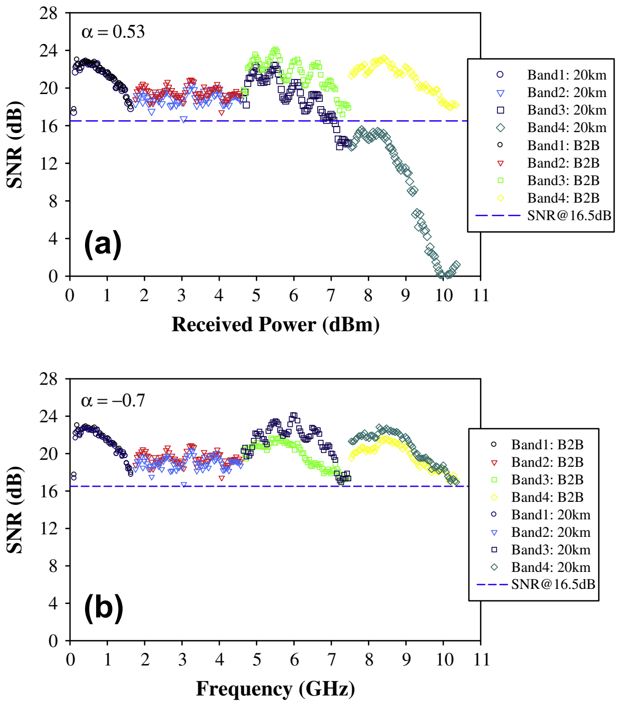

Fig. 4. Measured SNR of each OFDM subcarrier at the B2B and 20 km SMF transmission under the received power of −10 dBm, when (a) the 0.53 chirp parameter EAM and (b) −0.7 chirp parameters MZM is utilized respectively.

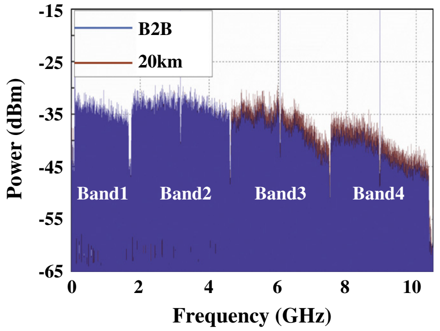

Fig. 5. Measured electrical power of four-band OFDM signal at B2B status and 20 km fiber transmission resepectively.

Fig. 6 shows the BER performances of downstream data traffic at the B2B status and 20 km SMF transmission. The total data rate of 28.75 Gbit/s can be obtained from OFDM band$_1$ to band$_3$. The Rx sensitivities of B2B status and 20 km SMF transmission are −17.1 and −17.4 dBm, respectively. The insets are the corresponding constellation diagrams at the B2B status and 20 km fiber transmission at the FEC level. As seen in Fig. 6, the negative power penalty of −0.3 dB is observed after 20 km fiber transmission by using a −0.7 chirp parameter of MZM. For the wireless signal broadcasting, the 8.945 GHz OFDM band$_4$ is also transmission. Here, Fig. 7 presents the BER performances of wireless traffic with 11.25 Gbit/s at the B2B status and 20 km SMF transmission. The power sensitivities of B2B status and 20 km SMF transmission are −16.7 and −17.1 dBm, respectively. And, the insets are the corresponding constellation diagrams at the B2B status and 20 km fiber transmission at the FEC threshold. As seen in Fig. 7, the negative power penalty of −0.4 dB is observed after 20 km fiber transmission. As a result, the measured negative penalty is due to the pre-chirp characteristic as discussed before.

Next, we will discuss the upstream traffic of the proposed TWDM-PON system. As illustrated in Fig. 2, a CW wavelength (λ_1') of 1550.50 nm is distributed from OLT and transmits through a BRF, EDFA, a 20 km SMF a BRF and an optical circulator (OC) launching into FP-LD of each ONU for mode-locking. Here, Fig. 8 shows the output spectrum of 2.5 GHz FP-LD (blue line) in free-run when the FP-LD is operated at the bias current and temperature of 30 mA and 25 °C. We observe that the maximum peak power of FP-LD is around 1550.55 nm in free-run. When the distributed CW lightwave is launched into FP-LD, the FP-LD would be injection-locked and could be direct modulated. According to the past study, to achieve a better output performance, the injection power into FP-LD should be larger −12 dBm [14]. Thus, Fig. 8 also illustrates the output spectrum of mode-locked FP-LD (red line) when an injection power is −12 dBm. The output wavelength and power of mode-locked FP-LD are measured at 1550.5 nm and −6.5 dBm respectively. Besides, the side-mode suppression ratio (SMSR) of 40.4 dB is also obtained, as shown in Fig. 8.

In this measurement, the upstream mode-locked FP-LD can be direct modulated by employing 16-QAM OFDM modulation to generate 10 Gbit/s upstream data rate. 5 GS/s sampling rate and 8 bit DAC resolution are set by the AWG, and CP of 8 is used. Thus, 128 subcarriers of 16-QAM format occupy nearly 2.5 GHz

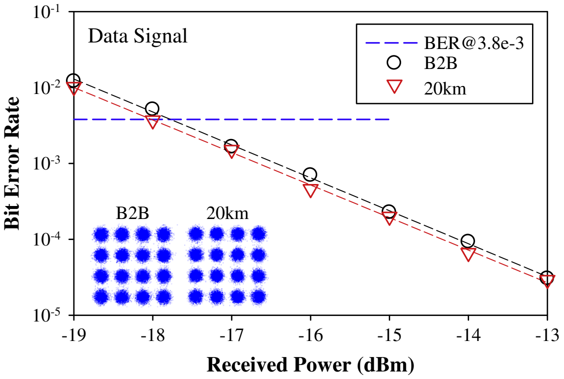

Fig. 6. BER performances of downstream data traffic at the B2B status and 20 km SMF transmission. And the insets are the corresponding constellation diagrams.

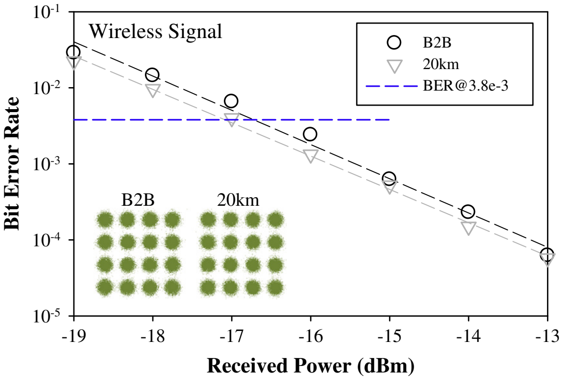

Fig. 7. BER performances of wireless traffic with 11.25 Gbit/s at the B2B status and 20 km SMF transmission. And the insets are the corresponding constellation diagrams.

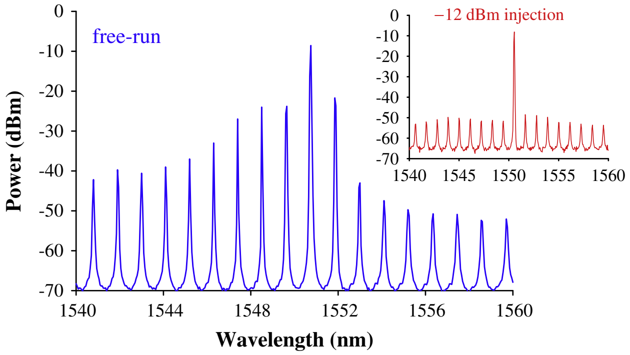

Fig. 8. Output spectra of 2.5 GHz FP-LD (blue line) in free-run and mode-locking (red line) when the FP-LD is operated at the bias current and temperature of 30 mA and 25 °C. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

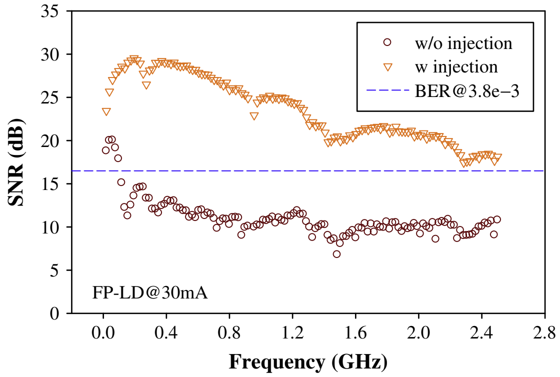

Fig. 9. Measured SNR spectra of each OFDM subcarriers after 20 km SMF transmission, when the FP-LD is without and with mode-locked operation.

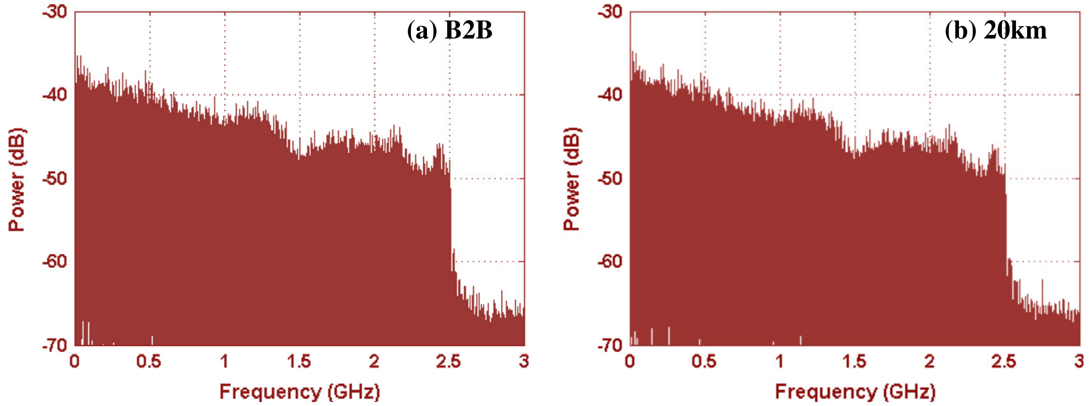

Fig. 10. Measured electrical spectra of the optical OFDM signal, when using −12 dBm injection power launching into the FP-LD, (a) at the B2B state and (b) after 20 km fiber transmission respectively.

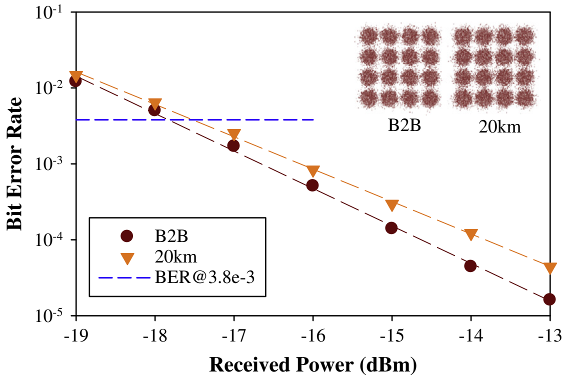

Fig. 11. BER performances of 10 Gbit/s 16-QAM OFDM upstream traffic at the B2B and after 20 km SMF transmission, respectively. And the insets are the corresponding constellation diagrams.

bandwidth from 0.0195 to 2.5195 GHz, with a fast-Fourier transform (FFT) size of 512. Here, 19.5 MHz subcarrier spacing and 10 Gbit/s total data rate are achieved. Hence, the produced electrical 16-QAM OFDM signal can be applied to the FP-LD via a bias-tee (BT). Then the upstream signal is direct-detected via a 2.5 GHz PIN Rx.

To realize the proposed upstream signal performance, we can measure the SNR of each OFDM subcarriers for the upstream traffic first. Fig. 9 shows the measured SNR spectra of each OFDM subcarriers after 20 km SMF transmission, when the FP-LD is without and with mode-locked operation. As illustrated in Fig. 9, the whole measured SNRs of mode-locked FP-LD can be larger than 16.5 dB (FEC threshold). To achieve 10 Gbit/s 16-QAM OFDM upstream transmission under standard reach of 20 km, the injection-locked FP-LD with −12 dBm injection power must be required. Besides, Fig. 10(a) and (b) shows the measured electrical spectra of the optical OFDM signal, when using −12 dBm injection power launching into the FP-LD, at the B2B state and after 20 km fiber transmission respectively. The FP-LD was dc-based properly. After 20 km fiber transmission, the electrical power would degrade in the higher frequency domain due to the power fading and fiber chromatic dispersion.

In the experiment, Fig. 11 presents the BER performances of 10 Gbit/s 16-QAM OFDM upstream traffic at the B2B and after 20 km SMF transmission, respectively. The insets of Fig. 11 are the corresponding constellation diagrams, measuring at the FEC threshold ($SNR = 16.5$ dB and $BER = 3.8 \times 10^{-3}$). Here, the Rx sensitivities are observed at −17.8 and −17.5 dBm, under the B2B state and 20 km fiber transmission, respectively. Therefore, the measured power penalty is ~0.3 dB, in the fiber transmission of 20 km.

OFDM is a multi-carrier modulation format and it is robust against fiber chromatic dispersion. This is because the symbol period of each subcarrier can be made long compared to the delay spread caused by the group-velocity dispersion (GVD). Previous, we have demonstrated that OFDM-QAM can be used in extended reach PON (100 km) without dispersion compensation [15]. Hence, the proposed approach in this paper can extended the transmission distance to 40 km.

3. Conclusion

We proposed and experimentally investigated a 115 (4 × 28.75) Gbit/s downstream and 10 Gbit/s upstream TWDM-PON system together with 11.25 Gbit/s wireless broadcasting at 8.945 GHz by using four-band OFDM modulation within 10 GHz bandwidth. Here, each OFDM channel was modulated at 16-QAM format. Here, there were four WDM downstream wavelengths and four distributed CW wavelengths in the CO. Each downstream wavelength carried 28.75 Gbit/s downstream data and 11.25 Gbit/s wireless signals simultaneously within 10 GHz bandwidth for TWDM-PON access. The four-band OFDM modulation was applied on a 10 GHz bandwidth MZM with −0.7 chirp parameter to compensate the power fading and fiber chromatic dispersion.

In the measurement, the direct-detection was used to reduce the cost of Rx side. Each 16-QAM OFDM channel only requires the 5 GS/s sampling rate and 5 bits resolution for the DA and AD conversion. Hence, negative penalties of −0.3 and −0.4 dB were measured experimentally for the downstream and wireless transmissions at the BER of 3.8×10^{-3} after 20 km fiber transmission respectively, when a −0.7 chirp parameter of MZM was used in the proposed four-band OFDM modulation for downstream link.

In addition, the distributed CW wavelength was utilized to launch into FP-LD-based ONU for injection-locking to serve as upstream traffic. Here, the measured upstream power penalty was 0.3 dB after a fiber transmission of 20 km, when an injection power of −12 dBm was injected into FP-LD. As a result, experimental and numerical analysis of using commercially available EAM and MZM with 0.53 and −0.7 alpha chirp parameter were performed, respectively, showing the pre-chirp MZM was very crucial for the proposed OFDM PON to reduce power fading and chromatic dispersion.

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